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Robust Feedback Control of Reconfigurable Multi-Agent Systems in Uncertain Adversarial Environments

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14. ABSTRACT
In this last period, our most exciting contributions pertain to algorithms for estimation and synchronization that are suitable to networked systems.
Motivated by the estimation algorithms with both performance and robustness guarantees developed during the second year of performance, we
proposed a hybrid observer that not only guarantees very fast performance but also total rejection of perturbations. The class of noise signals our
observer allows is given by the family of piecewise-constant signals with changes satisfying a dwell-time condition. A design procedure for the
observer is also provided for the estimation of the state of a single system, but preliminary results show that the algorithm can be extended to
networked systems. we also generated estimation and synchronization algorithms for two agents that operate under intermittent information. We
were able to devise algorithms that only require information about the (noisy) outputs of two systems at sporadic times to estimate their states and
synchronize them (asymptotically). The algorithms are dynamical (in fact, hybrid) and have a state variable that is appropriately reset at the arrival
of new information. The algorithms are also robust to small external perturbations, to skewed time clocks, and to infrequent packet drops.

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Accomplishments:

During the first review period, one of our most exciting contributions has been on the topic of distributed estimation with performance and robustness guarantees. The tradeoff between performance, namely, rate of converge of the estimates, and robustness to external disturbances (being measurement noise the most challenging disturbance to cope with) is a long standing limitation of state observers. Current linear observer structures that guarantee a fast rate of convergence of the estimates unavoidable amplify measurement noise. To overcome this limitation, we have proposed a new observer structure and design methodology, which we call “coupled multi-observers”, that, when compared to current linear observers, yield observers with improved rate of convergence and robustness to measurement noise. The new structure consists of multiple observers coupled in a clever way so that they observe the same process from different “viewpoints” and extract as much information as possible from the measurements. The design procedure is constructive and presented as computationally tractable optimization problems. Our new observer is an exciting breakthrough for the increasing need to estimate variables with good performance and robustness guarantees, especially when applied to distributed settings where uncertainty in the measurements is prominent. The other important contributions in this review period pertain to the use of hybrid methods in distributed settings and the design of numerical methods to properly compute their trajectories. We have generate results showing that hybrid observers can guarantee finite time convergence of the estimate with robustness, that synchronization (and desynchronization) of time in a network is a property that is robust to time skews and packet losses, and, for more general hybrid systems, we have developed constructive state-feedback laws for stabilization of compact sets.

During the second review period, our most exciting contributions have been on distributed robust estimation with performance guarantees and hybrid methods for the analysis and design of multi-agent systems. The tradeoff between performance, namely, rate of converge of the estimates, and robustness to external disturbances (being measurement noise the most challenging disturbance to cope with) is a long standing limitation in the design observers for single plants, which, unavoidable, is also a key limitation in estimation for multi-agent systems. To overcome this limitation, we have proposed a novel distributed observer structure and design methodology, which we call "interconnected observers", that, when compared to current distributed observers, yield local and global observers with improved rate of convergence and robustness to measurement noise as well as optimized communication graph. The new structure consists of distributed observers sharing information between nodes at the dynamic level, which is what differentiates our approach from other works where the information is shared at the output level through the computation of averages of the estimates. In fact, we were able to show that the average of the estimates does not alleviate at all the effect of worst case measurement noise. The design procedure of our interconnected observers is constructive and presented as computationally tractable multi-objective optimization problems.

During this period, our work on this topic was recognized by AACC as a finalist for the *Best Student Paper Computation at the 2014 American and Control Conference in Portland*. The other important contributions in this review period pertain to the use of hybrid methods for robust global stabilization of underactuated nonlinear systems and for the study of distributed hybrid systems. We have generate results establishing that hybrid backstepping techniques can be applied to design controllers for vector-thrusted vehicles that are robust to unmodeled dynamics, which is a key step toward the design of control algorithms for multiple vehicles. Hybrid methods were also applied to the analysis of distributed hybrid systems in the context of complex networks of spiking neurons for the study of synchronization and parameter sensitivity.

Also during the second period, our work on this topic was recognized by the *SIAM Control and Systems Theory Prize for contributions to analysis and syntheses of hybrid feedback control systems.*

During the third and last review period of this project, our most exciting contributions pertain to algorithms for estimation and synchronization that are suitable to networked systems. Motivated by the estimation algorithms with both performance and robustness guarantees developed during the second year of performance, we proposed a hybrid observer that not only guarantees very fast performance but also total rejection of a class of perturbations. More precisely, for linear time-invariant systems with noisy output measurements given by a function of the state, we designed an observer with state-triggered jumps that provides an estimate that converges to the true value of the state after tunable finite amount of time. The class of noise signals our observer allows is given by the family of piecewise-constant signals with changes satisfying a dwell-time condition. A design procedure for the observer is also provided for the estimation of the state of a single system, but preliminary results show that the algorithm can be extended to networked systems. The interest in finite time convergence has led us to the development of analysis and design tools for finite time stability for hybrid systems (single and multi-agents) with robustness, which is typically a missing link (for continuous-time, discrete-time, and hybrid systems). During this period, we also generated estimation and synchronization algorithms for two agents that operate under intermittent information. More precisely, we were able to devise algorithms that only require information about the (noisy) outputs of two systems at sporadic times to estimate their states and synchronize them (asymptotically). The algorithms are dynamical (in fact, hybrid) and have a state variable that is appropriately reset at the arrival of new information. The times that the transmission/reception of information occur has to satisfy some mild conditions that depend on the dynamics of each of the systems (especially if those are unstable). The algorithms are also robust to small external perturbations, to skewed time clocks, and to infrequent packet drop outs. More importantly, the modular nature of the algorithms suggests that they can be further developed to work in agents that are networked, heterogeneous and under the effect of perturbations. Such is the theme of our current proposal under review on estimation and synchronization in complex networks.

Archival publications:

<u>Submitted</u>: (7 journal and 9 conference submissions)

Zhang, K., Sprinkle, J. & Sanfelice, R. G., Computationally-Aware Switching Criteria for Hybrid Model Predictive Control Of Cyber-Physical Systems, Submitted to IEEE Trans. Automation Science and Engineering, 2015.

Smith, D. W. & Sanfelice, R. G., A Hybrid Control Strategy for Waypoint Transitioning and Loitering of Unmanned Aerial Vehicles, Submitted to the AIAA Science and Technology Forum and Exposition, 2015.

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Biemond, J. J. B., Heemels, M., Sanfelice, R. G. & Wouw, N. van de, Constructing distance functions and piecewise quadratic Lyapunov functions for stability of hybrid trajectories, Submitted to CDC, 2015.

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Chai, J. & Sanfelice, R. G., On Notions, Sufficient Conditions, and Feedback Control Design for Forward Invariance of Sets for Hybrid Dynamical Systems, Submitted to CDC, 2015.

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Sanfelice, R. G. & Praly, L., Solution of a Riccati Equation for the Design of an Observer Contracting a Riemannian Distance, Submitted to CDC, 2015.

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Naldi, R., Furci, M., Sanfelice, R. G., & Marconi, L., Robust Global Trajectory Tracking for Underactuated VTOL Aerial Vehicles using Inner-Outer Loop Control Paradigms, Submitted to IEEE TAC, 2014.

Published: (3 book chapters, 17 journal articles, and 40 conference articles)

Lou, X., Li, Y. & Sanfelice, R. G., On Robust Stability of Limit Cycles for Hybrid Systems With Multiple Jumps, To appear in Analysis and Design of Hybrid Systems (ADHS), 2015.

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Copp, D. A. & Sanfelice, R. G., On the Effect and Robustness of Zero-crossing Detection Algorithms in Simulation of Hybrid Systems Jumping on Surfaces, Proceedings of the American Control Conference, pp. 2449–2454, 2012.

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Mayhew, C. G., Sanfelice, R. G., Sheng, J., Arcak, M. & Teel, A. R., Quaternion-Based Hybrid Feedback for Robust Global Attitude Synchronization. IEEE Transactions on Automatic Control, 57, No. 8, pp. 2122--2127, August 2012.

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Abstract

In this last period, our most exciting contributions pertain to algorithms for estimation and synchronization that are suitable to networked systems. Motivated by the estimation algorithms with both performance and robustness guarantees developed during the second year of performance, we proposed a hybrid observer that not only guarantees very fast performance but also total rejection of perturbations. The class of noise signals our observer allows is given by the family of piecewise-constant signals with changes satisfying a dwell-time condition. A design procedure for the observer is also provided for the estimation of the state of a single system, but preliminary results show that the algorithm can be extended to networked systems. we also generated estimation and synchronization algorithms for two agents that operate under intermittent information. We were able to devise algorithms that only require information about the (noisy) outputs of two systems at sporadic times to estimate their states and synchronize them (asymptotically). The algorithms are dynamical (in fact, hybrid) and have a state variable that is appropriately reset at the arrival of new information. The algorithms are also robust to small external perturbations, to skewed time clocks, and to infrequent packet drops.

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Archival Publications (published) during reporting period:

Lou, X., Li, Y. & Sanfelice, R. G., On Robust Stability of Limit Cycles for Hybrid Systems With Multiple Jumps, To appear in Analysis and Design of Hybrid Systems (ADHS), 2015.

Chai, J. & Sanfelice, R. G., Hybrid Feedback Control Methods for Robust and Global Power Conversion, To appear in Analysis and Design of Hybrid Systems (ADHS), 2015.

Furci, M., Casadei, G., Naldi, R., Sanfelice, R. G. & Marconi, L., An Open- Source Architecture for Control and Coordination of a Swarm of Micro- Quadrotors, To appear in Proceedings of the International Conference on Unmanned Aircraft Systems (ICUAS), 2015.

Li, Y. & Sanfelice, R. G., Interconnected Observers for Linear Systems to Improve Rate of Convergence and Robustness to Measurement Noise, To appear in IEEE Transactions on Control of Network Systems, 2015.

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Changes in research objectives (if any):

N/A

Change in AFOSR Program Manager, if any:

N/A

Extensions granted or milestones slipped, if any:

N/A

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

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